

Large- x Parton Distributions

S. Kuhlmann,^a J. Huston,^b J. Morfin,^c F. Olness,^d J. Pumplin,^b J. F. Owens,^e
W. K. Tung,^b and J. J. Whitmore^f.

^aArgonne National Laboratory, ^bMichigan State University, ^cFermi National Accelerator
Laboratory, ^dSouthern Methodist University ^eFlorida State University, ^fPennsylvania State
University,

Reliable knowledge of parton distributions at large x is crucial for many searches for new physics signals in the next generation of collider experiments. Although these are generally well determined in the small and medium x range, it has been shown that their uncertainty grows rapidly for $x > 0.1$. We examine the status of the gluon and quark distributions in light of new questions that have been raised in the past two years about “large- x ” parton distributions, as well as recent measurements which have improved the parton uncertainties. Finally, we provide a status report of the data used in the global analysis, and note some of the open issues where future experiments, including those planned for Jefferson Labs, might contribute.

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1. Introduction

Four years ago the CDF collaboration reported [1] an excess of jet events at large transverse energy over perturbative Quantum Chromodynamics (QCD) calculations, *cf.*, Fig. 1. A possible explanation for this effect was a larger than expected gluon distribution at large x [2]. Three years ago the deep-inelastic scattering (DIS) experiments at HERA reported a low statistics excess of events at large Q^2 [3], *cf.*, Fig. 2. This led to speculation that part of this excess could be attributed to a lack of knowledge of the quark distributions at large x [4], and could possibly be related to the jet events which are produced by a combination of quark and gluon scattering. Both excesses produced a large number of papers about the possible implications for physics beyond the Standard Model, emphasizing the need for much better knowledge of parton distributions at large x .

In the past few years there has been considerable progress towards understanding some of the uncertainties in the individual measurements that contribute to our knowledge of large- x parton distributions (PDFs), but in some cases this has led to an *increase* in the uncertainty of the large- x PDFs, rather than a

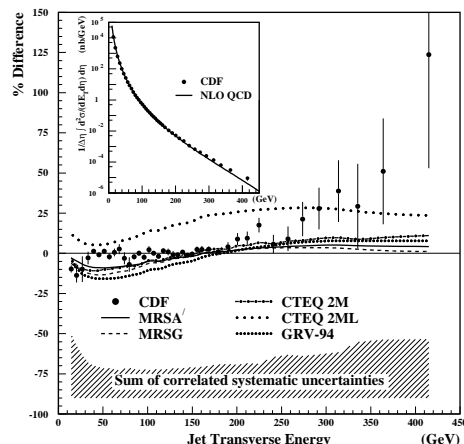


Figure 1. Comparison between the CDF inclusive jet cross section (points) and a next-to-leading order QCD predictions. Figure taken from CDF, Ref. [1].

reduction. We will review the recent analyses and point towards future measurements which may help clarify the situation. First we must better define “large x ”. For the gluon distribution there is little confusion: gluon distributions for $x > 0.1$ at all Q^2 become increasingly uncertain as shown in ref. [5], and further described below. The quark distributions are more complicated due to a strong Q^2 and flavor dependence. The incoherent sum of

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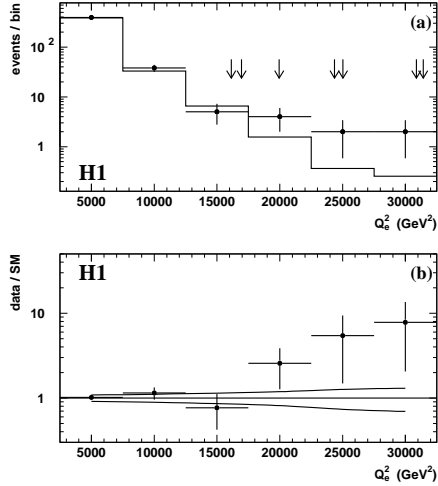


Figure 2. The Q^2 distribution of the selected neutral current DIS events for the data (points) and for standard model expectation (histogram). Figure taken from H1, Ref. [3].

quark distributions at moderate Q^2 (≈ 25 - 1000 GeV^2) is known to be well understood up to $x \approx 0.7$, but the earlier speculations [4] concerned large x ($x > 0.5$) and large Q^2 (> 10000 GeV^2). In addition, when one examines the individual flavors of quark distributions, the uncertainties grow significantly for $x > 0.3$. All of these issues will be discussed in detail, beginning with the gluon distribution.

2. Gluon Distribution

In the past few years there has been very little progress in reducing the uncertainty in the gluon distribution at large x , and new questions have arisen which perhaps confuse the situation even more. The most recent analyses of the gluon distributions from the CTEQ5 [6] and MRST [7] collaborations have reinforced the two conclusions of the earlier CTEQ4 gluon parameter scan [5], 1) that the gluon uncertainties for $x < 0.1$ are reasonably small and of order 10%, and 2) for $x > 0.1$ the uncertainties grow significantly. This is illustrated in Fig. 3, which shows the ratio of gluon distributions at $Q=100$ GeV to that of the CTEQ4M gluon distribution [8]. The

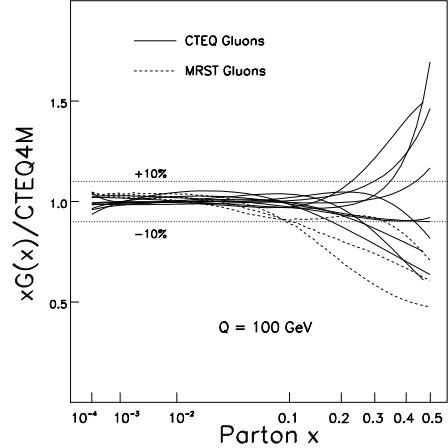


Figure 3. Ratios of gluon distributions are shown, compared to the CTEQ4M gluon distribution. The solid lines are distributions from the CTEQ4 and CTEQ5 analyses, and the dashed are from the MRST analysis (see text).

solid lines include both of the CTEQ5 gluon distributions (CTEQ5M and CTEQ5HJ), as well as the gluon distributions from the parameter scan mentioned above. The dashed lines are the three gluon distributions from the MRST analysis. One notices that the “bands” from CTEQ and MRST are quite consistent at low x , but barely overlap at large x .

What features of the CTEQ and MRST analyses cause the gluon discrepancy at large x ? This is due to the choices of different data sets used in each analysis, in particular the emphasis on Tevatron jet data by CTEQ and direct photon data by MRST. In addition, the specific treatment of the direct photon data with respect to the issue of k_t smearing [9] plays a significant role. The CTEQ and MRST groups agree that the direct photon theory needs some kind of correction for k_t smearing, but without a full theoretical framework the procedures for deriving such corrections are somewhat arbitrary, and are significantly different between ref. [9] and the MRST analysis. Therefore there are three scenarios that result in very different gluon distri-

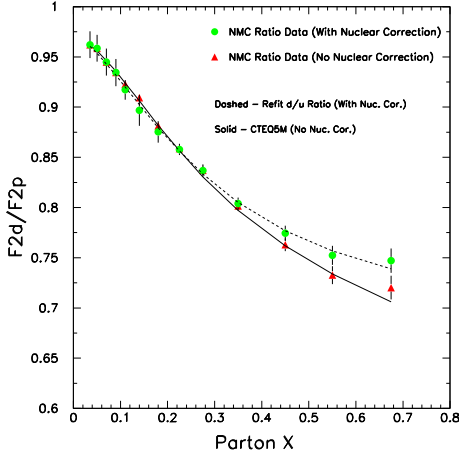


Figure 4. The measured ratio of muon scattering off deuterium and hydrogen targets, from the NMC experiment, is shown with and without the nuclear corrections described in the text. The solid line is CTEQ5M which was fit to the data with no nuclear corrections, while the dashed line is a fit to the data with the nuclear corrections, altering the d/u ratio (see text).

contributions: 1) Emphasis on the CDF collider jet data, which leads to the CTEQ5HJ set of parton distributions. These can be considered an upper bound to the gluon distribution at large x . 2) Emphasis on direct photon data and the k_t correction procedure of MRST. These can be considered a lower bound at large x . 3) Emphasis on direct photon data but using the k_t procedures of ref. [9]. This yields gluon distributions which are consistent with those such as CTEQ5M which tend to lie halfway between the two bounds. In addition, there are other complications in using both the direct photon and jet data sets. As pointed out in refs. [7][9], it is difficult to reconcile the k_t values needed by the WA70 and E706 experiments. The jet data, on the other hand, only used at transverse energies larger than 40 GeV, should not be significantly affected by k_t . These measurements and comparisons to theory have their own set of concerns. Included in these is the definition of the jet,

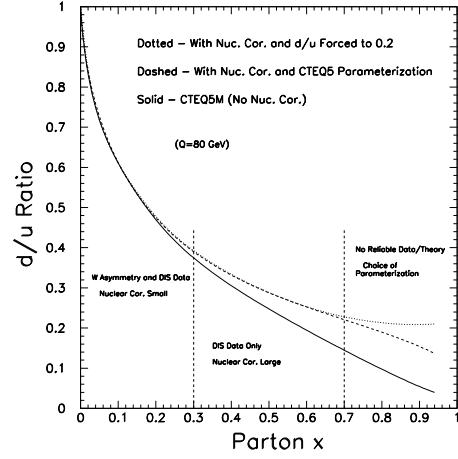


Figure 5. The d/u ratio is shown for the three global fits described in the text. Also shown are the three different regions of x and the relevant measurements in each region.

which can never be exactly the same in the data and in a next-to-leading-order QCD calculation. The precise statistical procedure for the jet data, which are dominated by highly correlated systematic uncertainties, is another area of concern [10].

Clearly much more work is needed on the gluon distribution at large x : what can be done to improve the constraints? Obviously the best scenario is a complete understanding of soft gluon effects in the direct photon data sets, in which case the E706 data are sufficiently precise to severely constrain the gluon distribution. This may take many years, however, and the discrepancies between data sets may never be understood. In addition, more work is needed on the Tevatron jet data and their interpretation, especially the recent differential dijet measurements from both CDF and D0. These data are also sensitive to changes in the quark distributions, discussed in the next section. Finally, another possibility for a future measurement is to use the Drell-Yan process to measure the large- x gluon distribution at the Fermilab Main Injector, as discussed in ref. [11]. Acquiring the needed data set for this measurement is more

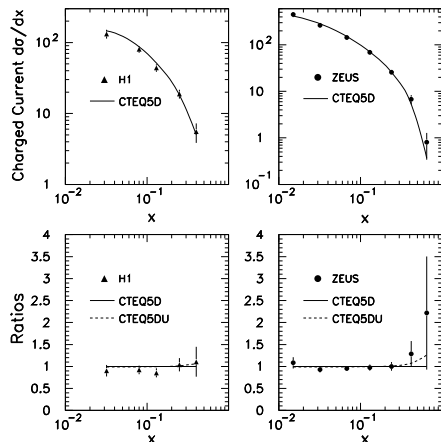


Figure 6. Positron-induced charged current data from H1 and ZEUS are shown, along with NLO QCD calculations using parton distributions fit with and without nuclear corrections to the fixed target data (see text).

speculative, but appears to be worth a serious study of the potential of such an experiment.

3. General Quark Distribution Issues

There are four main ways that large- x quark distributions may be modified in a significant way (enough to affect Tevatron and/or HERA processes), while maintaining agreement with fixed target data sets: 1) a modification of the u quark near $x \approx 1$, 2) a non-perturbative “intrinsic charm” type of component that is presently assumed to be zero, 3) a modification of the d quark at large x , and 4) higher twist contributions that are missing from the conventional fits to the low Q^2 fixed target data. The first three were discussed in ref. [4], where an example toy model of a modified u quark distribution was presented. Much more is now known about the constraints on such models, as will be discussed next. The d quark issues will be discussed in detail in the next section.

The first “new” constraint is the reanalysis of large- x SLAC electron scattering data off hydrogen targets, discussed in ref. [12].

This data set is in the resonance region and one must assume that the Bloom-Gilman duality hypothesis [13] can be applied. In addition, these data require target mass corrections that are enormous, up to a factor of 50 near $x \approx 1$. The target mass corrections are mostly derived by using the Nachtmann scaling variable instead of x [12], and are a fairly straightforward kinematic shift due to the mass of the proton. The duality hypothesis and target mass corrections are probably accurate enough to constrain modification #1 above, but one would like another measurement/process to confirm these assumptions. In addition, these data are below the charm threshold and therefore say nothing about intrinsic charm models. A recent neutrino scattering measurement from CCFR [14] appears to provide some confirmation of the electron analysis. These data are also at higher Q^2 and therefore above the charm threshold. A concern with this measurement is the nuclear effects from the iron target. But with relatively simple Fermi motion corrections, the data are within a factor of 2 of predictions using conventional parton distributions of the nucleon such as CTEQ4M. The comparison can be further improved with more sophisticated treatments of the nuclear effects. The combination of the neutrino and electron data analyses makes it unlikely that either of the first two modifications of the quark distributions are large enough to affect collider measurements.

Phenomenological fits for higher twist effects are described in refs. [15][16], while one theoretical model for the parton-parton correlations involved is discussed in ref. [17]. Both the model and the fits show $\approx 3\%$ changes in the valence quark distributions in the $0.1 < x < 0.5$ range, growing to 5-10% changes at $x \approx 0.8$. The changes described in these papers should also be considered as part of the uncertainty in the parton distributions.

4. d/u Ratio

The ratio of the density of down quarks to that of up quarks in the proton has changed in the most recent CTEQ and MRST analy-

ses due to the new W lepton-asymmetry data from CDF [18], as well as the NMC ratio measurement of deuterium/hydrogen scattering [19]. For many years the basic assumptions about the parameterization of this ratio and the use of the DIS data have been relatively unchallenged, but this has changed. The two main reasons to question these assumptions are: 1) the behavior of the d/u ratio as $x \rightarrow 1$, and 2) possible nuclear binding effects in the deuteron. We will now review some of the history of these two issues.

The extrapolation of the d/u ratio was discussed in non-perturbative QCD-motivated models in the 1970's such as ref. [20]. These models predicted that the ratio should approach 0.2 as $x \rightarrow 1$. Other models predicted the ratio should go to zero; but since neither is convincing the asymptotic value of this ratio has been set arbitrarily by the choice of parameterizations of the CTEQ and MRS groups. The choices that were made drive the ratio to zero as $x \rightarrow 1$. Some papers in recent years, such as ref. [21], have called for a special set of parton distributions that force the ratio to 0.2 as an alternative to the standard sets. Such a fit has now been performed and will be discussed below.

More than five years ago the SLAC experiment E139 published a series of measurements [22] with different targets. One of the goals of the measurement was to see if nuclear binding effects were present in deuterium. This was accomplished by a global fit to all the target data, within the context of a non-perturbative nuclear density model [23]. The conclusion was that the binding effects clearly seen in heavier nuclei are also present in deuterium at the few percent level. This result is not surprising, and is perhaps even expected, but it is not conclusive for two reasons: 1) it depends critically on an unproven nuclear physics model with many parameters that had to be obtained from fits to the data, and 2) the deuteron is a very special nucleus with binding energies much smaller than the rest, so that a large extrapolation from the heavier nuclei is needed. Ref. [24] argues that a proper extrapolation predicts no binding effects in the deuteron. With the caveats

just mentioned we consider the corrections to have a large and unquantified uncertainty.

The effects in the previous two paragraphs were ignored until the analysis of Yang and Bodek [12] two years ago. They took the latest W lepton-asymmetry and NMC ratio data and proposed a modification of the d/u ratio that included the nuclear binding effects and forced the ratio to 0.2 as $x \rightarrow 1$. This proposal has fueled considerable interest in these issues. However, the paper implied that the W lepton-asymmetry and NMC ratio data could be fit *only* with the nuclear binding corrections *and* with $d/u \rightarrow 0.2$ as $x \rightarrow 1$, which we will show is not the case. In fact, both data sets can be fit quite well without *either* modification.

To illustrate the different possibilities, a new series of fits was performed within the context of the CTEQ5 global analysis [6]. The nuclear binding corrections were included as well as fits with a modified behavior of d/u as $x \rightarrow 1$. We find we can get a good fit to all the data with neither correction, or with the nuclear binding corrections added but with any d/u behavior as $x \rightarrow 1$. Figures 4 and 5 show examples of this. Figure 4 shows the NMC ratio data with and without the deuteron correction. The lower (solid) curve is CTEQ5M, while the upper (dashed) curve is a new fit to the corrected data, again with the standard CTEQ5 parameterization which forces d/u to zero as $x \rightarrow 1$. Both are good fits to the NMC data, as well is a new third option (not shown since it lies precisely on the dashed curve) which includes both the nuclear corrections and the changed d/u parameterization.

Figure 5 shows the d/u ratio resulting from these three fits at $Q=80$ GeV (there is very little evolution dependence in this ratio). All three are viable candidates for the d/u ratio, and the upper and lower ones could quite reasonably be considered upper and lower bounds. Figure 5 also includes vertical lines to distinguish the three regions of x involved in this study, and to help explain why the different effects can be treated as independent. For $x < 0.3$ the W lepton-asymmetry data and the NMC ratio data are both very precise *and*

the nuclear corrections to the NMC data are insignificant. The two measurements agree so the d/u ratio is very well constrained in this region. Unfortunately the present W asymmetry data end near $x = 0.3$, precisely where the nuclear corrections to the NMC data become significant. Therefore with any reasonably flexible parameterization one can get a spread of d/u ratios for $0.3 < x < 0.7$ (the middle region of the plot) simply by changing the nuclear correction, and still fitting the W asymmetry and NMC data. Finally for the largest x values, we note that the NMC data end near $x = 0.7$; therefore many different extrapolations to $x \rightarrow 1$ are possible, with or without nuclear corrections. Clearly the issues for the three different regions are quite independent.

It is worth noting that if $d/u \rightarrow 0.2$ as $x \rightarrow 1$, then there *must* be some nuclear corrections in order to fit the NMC data. The previous discussion shows that the converse is not necessarily true. However if appreciable binding effects are present in the deuteron, then it is perhaps more natural for d/u to go to a constant than to zero, which would require a fairly sharp downturn near $x = 1$. Assuming that d/u does not suddenly increase as $x \rightarrow 1$, this constant is unlikely to be larger than 0.22, since that is where the last NMC data point lies. But any constant between 0.05 and 0.2 would be a reasonable extrapolation and is not constrained by present data. The only bias is the theoretical one mentioned earlier for 0.2, which we do not find persuasive.

One possible way to constrain the d quark is from measurements of π^+/π^- production in DIS interactions, as described in ref. [25]. But certainly the best way to constrain the d quark in the future, in terms of both experimental and theoretical uncertainties, is with high luminosity HERA measurements of positron-induced charged current interactions. The upper two plots in Figure 6 show the most recent H1 [26] and ZEUS [27] charged current measurements. For the H1 data the cuts are $Q^2 > 1000 \text{ GeV}^2$ and $y < 0.9$, while for ZEUS the cut is $Q^2 > 200 \text{ GeV}^2$. They are compared to a NLO QCD calculation using the standard CTEQ5D (DIS scheme) set of parton distribu-

tions, which are fit without the binding corrections to the NMC data. The lower two figures show the ratios (solid curves) with respect to the theory using CTEQ5D. This provides a good description of the data, although there is a hint of a low statistics excess in the ZEUS data. The dashed curves in the ratio plots are a second DIS scheme fit, which we label CTEQ5DU, including binding corrections but with the CTEQ5 parameterization ($d/u \rightarrow 0$) corresponding to the dashed curve (in the \overline{MS} scheme) in Figure 5. Since the data are below $x < 0.7$ the fits with $d/u \rightarrow 0.2$ give the same result as CTEQ5DU in this plot. Parton distributions similar to the dashed and solid curves were used to estimate the required luminosity to distinguish them. The result is that 500 pb^{-1} of delivered positron luminosity (250 pb^{-1} in each of the two experiments) [28] is needed to achieve a 2 standard deviation separation. This is clearly a large data set but not impossible with the forthcoming HERA upgrade. We think it is vital that the HERA program continue until this issue is settled.

5. Global Analysis: Present Status

This last section provides an overview of the improved and new data used in the latest CTEQ5 global analysis since the CTEQ4 analysis.[8] The situation is summarized graphically in Fig. 7.

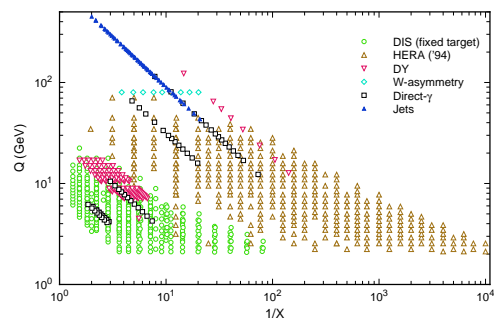


Figure 7. Kinematic map in $\{x, Q\}$ space of the data sets used in the CTEQ5 global analysis. Figure taken from CTEQ5, Ref. [6].

Deep inelastic scattering: The NMC and CCFR collaborations have finished and published analyses of their respective data on muon-nucleon [19] and neutrino-nucleus [29] scattering. These new results lead to subtle changes in their implications for α_s and parton distribution determination. The H1 and ZEUS collaborations at HERA have published more extensive and more precise data on the total inclusive structure function F_2^p [30, 31]. These results provide tighter constraints on the quark distributions, as well as on the gluon distribution, mainly through the Q -evolution of the structure functions. The HERA experiments also present new data on semi-inclusive F_2^c , with charm particles in the final state [32, 33].

Lepton-pair production (p/d) asymmetry: The E866 collaboration has measured the ratio of lepton-pair production (Drell-Yan process) in pp and pd collisions over the x range $0.03 - 0.35$ [34], thus expanding greatly the experimental constraint on the ratio of parton distributions \bar{d}/\bar{u} (compared to the single point of NA51 at $x = 0.18$ [35]). This data set has the most noticeable impact on the new round of global analysis.

Lepton charge asymmetry in W -production: The CDF collaboration has improved the accuracy and extended the y range of the measurement of the asymmetry between $W \rightarrow \ell^\pm \nu$ at the Tevatron [36]. This provides additional constraints on d/u .

Inclusive large p_T jet production: The D0 collaboration has recently finished the final analysis of their inclusive jet production data, including information on the correlated systematic errors [37]. The CDF collaboration also has presented new results from their RunIB data set [38]. Systematic errors in these data sets dominate the experimental uncertainty over much of the measured p_T range. The correlated systematic errors provide important information on the shape of the differential cross-section, $d\sigma/dp_T$, and constrain the parton distributions accordingly.

Direct photon production: The E706 collaboration at Fermilab has published the highest energy fixed-target direct photon production data available to date [39]. The mea-

sured cross-sections lie a factor of $2 - 3$ above the traditional next-to-leading (NLO) QCD calculation, thus posing a real challenge for their theoretical interpretation and their use in global analysis.

6. Conclusions

The goal of this workshop was, in part, to identify areas where the Jefferson Lab experiments could make a substantive contribute to our understanding of hadron structure. In examining Fig. 7 there are a number of obvious kinematic regions where the unique characteristics of Jefferson Labs might provide an advantage. Most evident in Fig. 7 is the cut on the data for $Q > 2$ GeV. While this cut serves to minimize the influence of higher-twist contributions, it also excludes a large quantity of data. Any effort that would allow us to include the lower Q data without introducing such uncertainties would be welcome.

The second feature we note regarding Fig. 7 is the limited Q -span of the data in the large x region.² In this region we face issues of higher-twist, nuclear corrections (as discussed above), and resummation of $\ln(1 - x)$ terms. Again, this is a kinematic region that provides both experimental and theoretical challenges.

Finally, let me comment on one very interesting possibility that was discussed at this meeting—DIS from a Tritium target. Using, in part, comprehensive DIS data from H (p) and D (pn) targets we try to decompose this information to obtain structure functions for the proton and neutron. However, there are many assumptions and potential pitfalls (including nuclear corrections discussed previously) that can enter. Consequently, it would be valuable to have additional information from Tritium (pnn) to help disentangle this process.

In recent years, new information has become available concerning large- x parton distributions and their uncertainties. The issues have become more important with the realization that these uncertainties could be hampering searches for physics beyond the Stan-

²While Fig. 7 does faithfully show the $\{x, Q\}$ points, it does not represent the comparative uncertainties.

dard Model. The different analyses reviewed in this letter have clarified some of the issues, but have also raised new questions to be addressed. We have outlined a program of measurements, as well as important theoretical work, that is needed to improve the uncertainties in large- x parton distributions.

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